H-infinity Control for European Telecommunication Satellites

Artist's rendering of Eutelsat W2A satellite in orbit, based on the Spacebus 4000 C4 platform, with deployed solar arrays and 12-m-diameter antenna (Source: Thales Alenia Space)

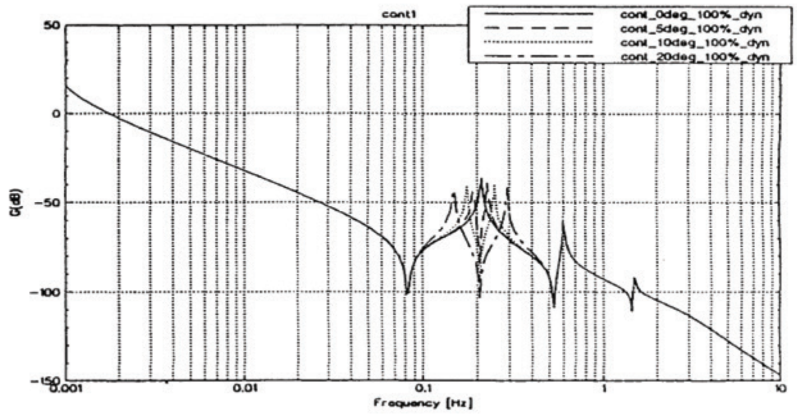
In the early 1990s, European space industries initiated research in robust control, specifically H-infinity (H_∞), through close collaboration with external control laboratories. The research was motivated not only by the desire to gain experience in this new method, but also to evaluate its potential benefits, performance improvements, and development costs when compared to traditional (proportional-integral-derivative and linear-quadratic-Gaussian) controllers commonly used in the 1980s. The increasing performance and dynamic complexity of future space applications were also a source of motivation for the research program on robust control techniques.

The transfer of robust control techniques from research laboratories to industrial space applications covered not only the technique itself, but also the process-oriented engineering tools and methodologies required for modeling, design, and analysis of robust H_∞ controllers.

Telecommunication Satellite Control System Design: Challenges and Needs

Geostationary telecommunication satellite platforms typically consist of a central body and large (deployable) antennae together with low-damping flexible solar arrays that are rotating with respect to the Earth-pointing central body at a rate of one rotation per day. During orbit inclination correction maneuvers, the satellite is submitted to thruster-induced disturbance torques that require some few tens of nanometers control authority to limit the attitude depointing below 0.1 deg. Because of the low damping (typically 10^{-3}) and shifting frequency modes with high resonant peaks of the large rotating solar arrays (see figure below), a stiff filtering controller is required. Using classical control design techniques, the design problem is solved in an ad hoc fashion requiring skilled engineers to initiate the lengthy iterative design procedures, tune the convergence control parameters, and balance the multi-objective performance index.

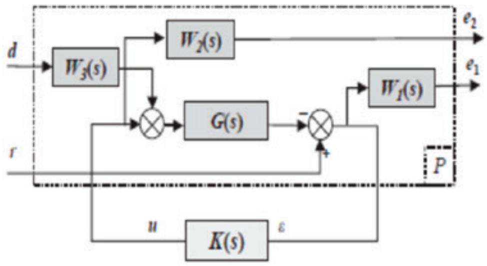
The limited capability of the classical design procedures to adapt to other space control problems prompted the need to develop automated control design techniques, including systematic procedures to rapidly adapt to changes in dynamic models, to rapidly optimize performance under constraints of parameter uncertainties, and to address "flexible structure control" formulations in the frequency domain. From an industrial perspective, there was also a need to improve European system integrators' competitiveness within the global space market by reducing the overall telecommunication satellite development time. H_∞ techniques enabled fulfillment of these requirements.



Structural flexible modes (above) of the Astrium communication satellite platform Eurostar 2000+ (left). The shifting of frequency modes corresponds to different angular positions of the solar arrays. (Source: EADS)

Contributor: Christian Philippe, European Space Agency, Netherlands

From: *The Impact of Control Technology*, 2nd ed., T. Samad and A.M. Annaswamy (eds.), 2014. Available at www.ieeecss.org.

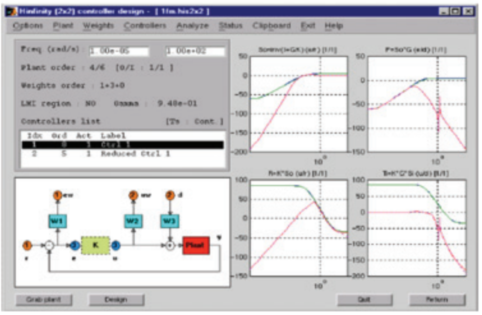


Standard four-block H_∞ scheme (Source: Thales Alenia Space)

Standard Four-Block H_∞ Scheme

The standard four-block H_∞ problem corresponds to the scheme shown on the left, where e_1 and e_2 are signals to be controlled with respect to reference input r and disturbance input d. The closed-loop control objectives are attained through an appropriate tuning of the weighting filters $W_i(s)$ chosen to shape the four transfer functions from r and d inputs to ε (control error) and u (command) outputs. The weighting filters are tuned to ensure good reference tracking and disturbance rejection as well as to meet the desired control bandwidth and rolloff attenuation of the flexible structural modes. The H_∞ problem consists of finding the controller K(s) that fulfills the four main control design objectives:

1. Guaranteeing stability margins
2. Filtering flexible structural modes from solar arrays and/or antennas and propellant sloshing modes
3. Minimizing the attitude degradation in the presence of external and internal disturbances
4. Minimizing sensor noise transmission and fuel consumption



Ready-to-use engineering software tool based on MATLAB from MathWorks (Source: Thales Alenia Space)

The standard four-block H_∞ scheme benefits from attractive numerical and physical properties and analytically guarantees the stability margin and robustness. Although the scheme offers an all-in-one design procedure, it must be used in association with order-reduction techniques to obtain the final controller. The all-in-one approach prevents the designer from having to do repeated iterations between preprocessing, optimal design, and post-processing, as experienced in the classical control design procedure. The all-in-one control design procedure has been implemented in a ready-to-use engineering software tool based on MATLAB from MathWorks and in dedicated control toolboxes (see figure at left).

Benefits

The development of H_∞ controllers for European telecommunication satellite platforms such as Eurostar 3000 and Spacebus 4000 has helped reduce the duration of the orbit inclination correction maneuver by 50%, equivalent to a propellant mass savings of about 20% when compared to the classical control design technique based on proportional-integral-derivative control combined with specific filters in the flexible-modes frequency range.

Ariane 5 launcher (top) and SILEX (bottom) (Source: EADS Astrium)

Other Real-World Applications

H_∞ controllers have also been developed, implemented, and successfully flown on the Ariane 5 Evolution launcher, the Automated Transfer Vehicle (ATV), and earth observation, scientific, and exploration satellites, as well as pointing, acquisition, and tracking (PAT) systems. The benefits of applying H_∞ control techniques for Ariane 5 and the first European optical communication terminal in orbit (SILEX) are summarized below:

Ariane 5 Evolution Launcher

- Issue: structural bending and sloshing modes
- H_∞ controller synthesis (atmospheric phase)
- Benefit: thrust vector control actuation effort minimized

Optical Laser Terminal (PAT)

- Issue: performance limitations of traditional controller
- H_∞ controller synthesis (tracking mode at 20 Hz)
- Benefit: pointing stability performance of 0.1 µrad

For more information: B. Frapard and C. Champetier, H_∞ techniques: From research to industrial applications, Proc. 3rd ESA International Conference, Noordwijk, Netherlands, November 26-29, 1996; G. Pignie, Ariane 5 and Ariane 5 evolution GN&C overview, 34th COSPAR Scientific Assembly, The Second World Space Congress, Houston, TX, October 10-19, 2002; C. Charbonnel, H_∞ and LMI attitude control design: Towards performances and robustness enhancements, Acta Astronautica, vol. 54, pp. 307–314, 2004.